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TECHNICAL REPORT ECOM-01758-6

GUNN EFFECT DEVICES

SIXTH QUARTERLY TECHNICAL REPORT

By

J. BARRERA

AUGUST 1967

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GUNN EFFECT DEVICES

SIXTH QUARTERLY TECHNICAL REPORT
15 March 1967 to 15 June 1967

Report No. 6

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for

U. S. Army Electronics Command, Fort Monmouth, New Jersey

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ABSTRACT

A comparison is made of the latest Hewlett-Packard Laboratories fabricated GaAs Gunn effect devices (TE113's) with the best previous devices (TE65's). A slight improvement in power output has been achieved along with a considerable lowering of device FM noise. Along with microwave and noise measurements, preliminary results of a simplified computer study on the bulk negative resistance mode of operation is given.

PURPOSE

A development program is to be conducted aimed at the utilization of the Gunn effect for various types of microwave generating devices in the 1 to 50 GHz frequency range. Spectral line width should be less than 10kHz and operation should be in a single mode. Output power should be at least 25 mW in CW operation and 3W peak in pulsed operation with a conversion efficiency of at least 3%. CW operation should be obtained in ambient temperatures from -25°C to +50°C with a single device.

Application of these devices for amplification and modulation is to be investigated.

FOREWORD

The work reported on in this report has been authorized by the Contracting Officer, Mr. Edgar D. Fitzgerald, Electronic Components Laboratory, U. S. Army Electronics Command, Ft. Monmouth, New Jersey, under Contract No. DA 28-043 AMC-01758(E) and titled "Gunn Effect Devices". The Project Engineer at the U. S. Army Electronics Command is Mr. Maurice Druesne.

The work has been performed at Hewlett-Packard Laboratories under the supervision of M. M. Atalla. The report has been prepared by J. Barrera. Significant contributions during the report period have been made by M. L. Wright, N. Mantena, G. W. Mathers, E. Gowan and B. Farrell. Discussions with M. M. Atalla and C. F. Quate were of great benefit.

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GUNN EFFECT DEVICES

SIXTH QUARTERLY TECHNICAL REPORT

I.   DEVICE FABRICATION AND MEASUREMENTS

I. 1   Introduction

During the past quarter, effort has been made to improve the quality of HPL solution-grown material and to optimize the performance of devices made from it.   Of the many samples processed the best performance to date was given by a group of devices designated as TE 113's.   The starting material had a resistivity of 1. 5 Ω cm, a room temperature mobility of 8700 cm^2/V sec and a carrier density of 4. 9 x 10^{14} cm^{-3}.

I. 2 Performance Summary

A summary of the characteristics of TE 113's is given in Table I below. The RF evaluation was made with the devices in a fixed tuned coaxial cavity with multiple resonances at approximately 13, 10.5, 8.5, 6.0 and 3.5 GHz. In addition, about 25 TE 65 devices (the best previous devices) have been tested in the same cavity for a more direct comparison.

TABLE I

Device Designation:		TE 65	TE 113
No. of samples tested		25	37
Resistivity (Ω cm)		0.9	1.5
Temperature Coeff. of resistance		Positive	Positive
Thickness (microns)		20-25	14-20
Contact Dot diameter (microns)		75	105
Threshold Voltage (volt)		6.5-8.5	5.0-6.5
Threshold Current (ma)		70-90	90-130
Operating Frequency (GHz)	1)	8.7-8.9	8.0-8.4
	2)	6.2-6.3	6.1-6.2
RMS Frequency Deviation in 1KHz BW, 10 KHz from the Carrier (sec^{-1}) (voltage range)		300 @ 8.7 GHz (8-10)	50 @ 8.3 GHz (10-16)
		120 @ 6.2 GHz (10-12)	24 @ 6.15 GHz (16-20)

As can be seen from Table I the FM noise behavior for the TE 113's is quite good with an RMS frequency deviation of less than 4 parts in 10^9 at 6.15 GHz.

I. 3   RF Power Output

Several TE 65 samples have been tested in the tunable coaxial cavity (4-8 GHz) described in the previous quarterly report. The results show a significant difference in the maximum power output obtainable under CW and pulsed operation. Output curves for a typical TE 65 device are shown in Figure 1.

The relatively lower power output for CW operation appears to be due almost entirely to thermal effects. That is, the same power drop could be obtained under pulsed operation by externally heating the cavity or by increasing the duty cycle.

Preliminary results on a TE 113 sample operated in the same cavity as above are shown in Figure 2. As indicated, the same behavior as for TE 65's was found.

I. 4   New Cavity Design

A new ridge guide cavity has been designed, built and assembled. This cavity operates in a $\lambda/2$ mode over the frequency range 6-12 GHz. The design is such that the sample may be positioned anywhere along the cavity and the loading can be adjusted over a wide range. It is hoped that the RF performance can be optimized more easily with the new design and as preliminary tests with some TE 113 samples have shown, it is operating quite favorably.

I. 5   Discussion

Effort is continuing on the complete evaluation of assymetrical Gunn Effect devices made from HPL solution-grown GaAs material. The present
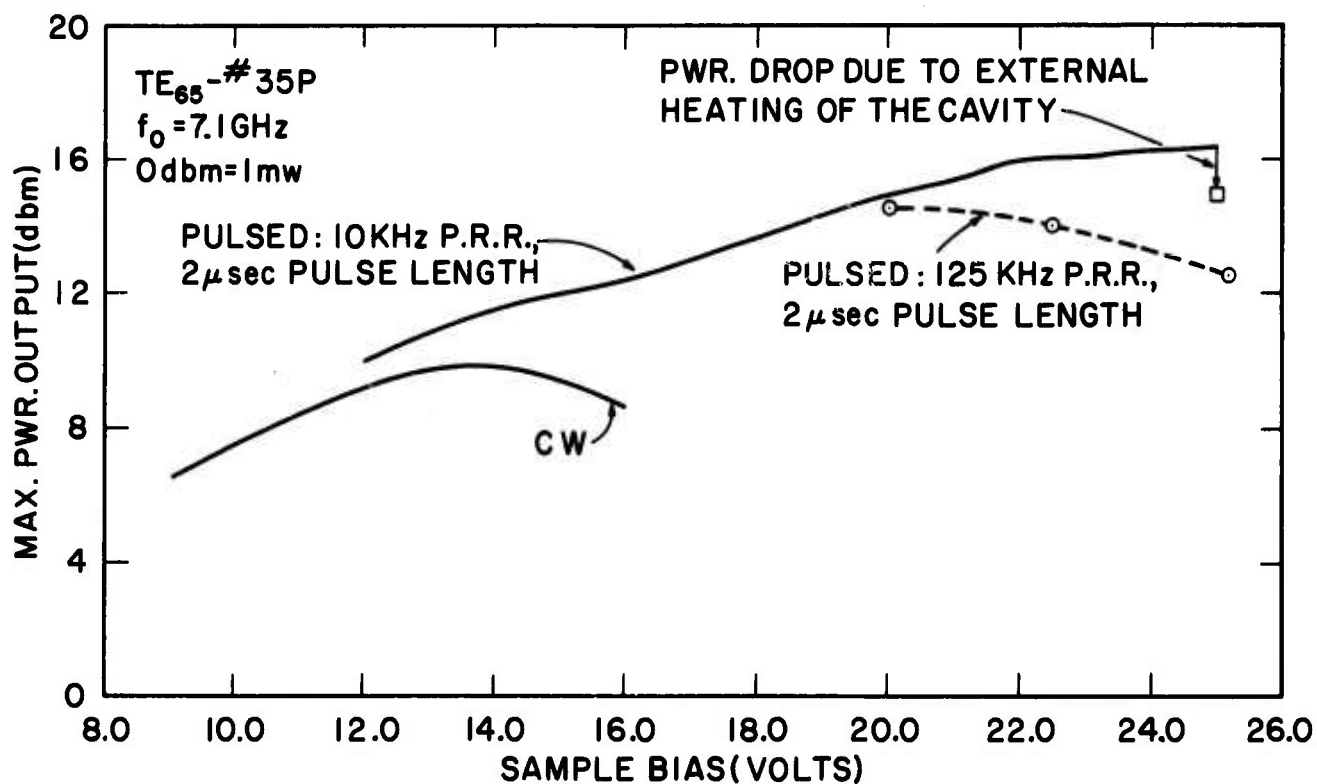
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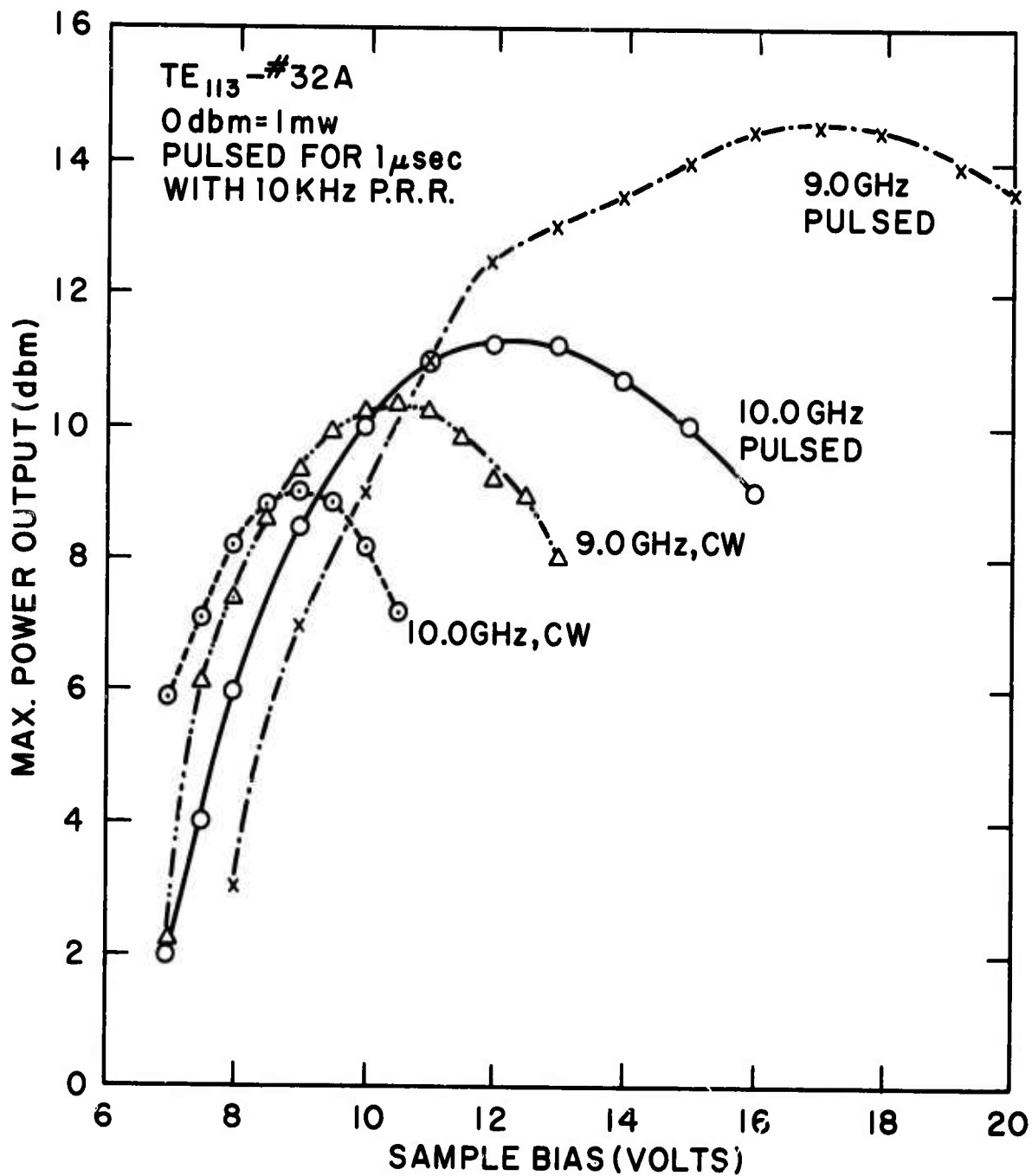FIGURE 1: TYPICAL MAXIMUM POWER OUTPUT
FOR TE 65 DEVICES

FIGURE 2: PRELIMINARY CW AND PULSED MAX. POWER
OUTPUT FOR A TE 113 DEVICE

devices are very consistent in behavior and are improving with each new group tested. The mounting of samples is such that a continuous DC power input of 3 to 6 watts can be safely handled.

It is felt that the symmetrical device should next be studied in an effort to improve the power efficiency and to provide a more stable geometry for the "LSA" mode of operation. There are at present indications that the asymmetrical geometry presently being used is forcing the devices to operate in an essentially "stationary" domain mode. This mode is reflected in the relatively low efficiencies so far obtained and also in the very small direct current drops at and above threshold. A study is underway to understand the actual mode of operation for the asymmetrical device geometry and to explore fully the limitations of present devices.

With regard to the pulsed and CW power curves of Figure 2, it should be noted that at lower bias voltages the CW curves are higher than the pulsed curves. This was due to a 1 to 2 μsec time constant associated with the RF power buildup during the pulse. At higher bias the effect was not as pronounced and an essentially constant power output was obtained for pulses of 0.5 to 10 μsec duration.

II.   NOISE MEASUREMENTS

II. 1   Current Noise Studies

a. Contact Noise

The 1/f type current noise observed below threshold bias is supposed due to the device contacts. The best accepted model for conductivity modulation, 1/f type, contact noise involves a very slight or non-existent temperature dependency. Consequently, the room temperature and 77°K current noise was measured and was found to indeed be nearly independent of temperature. The noise spectra at 300°K and 77°K for sample TE65-B3 are shown in Figure 3. In order to compare the noise at the two different temperatures, the noise ratio, n, is computed. This noise number will effectively normalize the noise with respect to resistance changes--all other parameters being the same. That is

$$n = \frac{i^2/\Delta f}{4kT/R}$$

where $i^2/\Delta f$ is the mean square short circuit current noise per cycle bandwidth, T the temperature, k the Boltzmann constant and R the device resistance. From Figure 3 it is seen that both spectra have the same frequency dependence and, therefore, it is sufficient to calculate $n_{(T, R)}$ for just one frequency. Thus,

$$n_{(300°K, \ 42\Omega, \ 4 \ KHz)} = 210$$

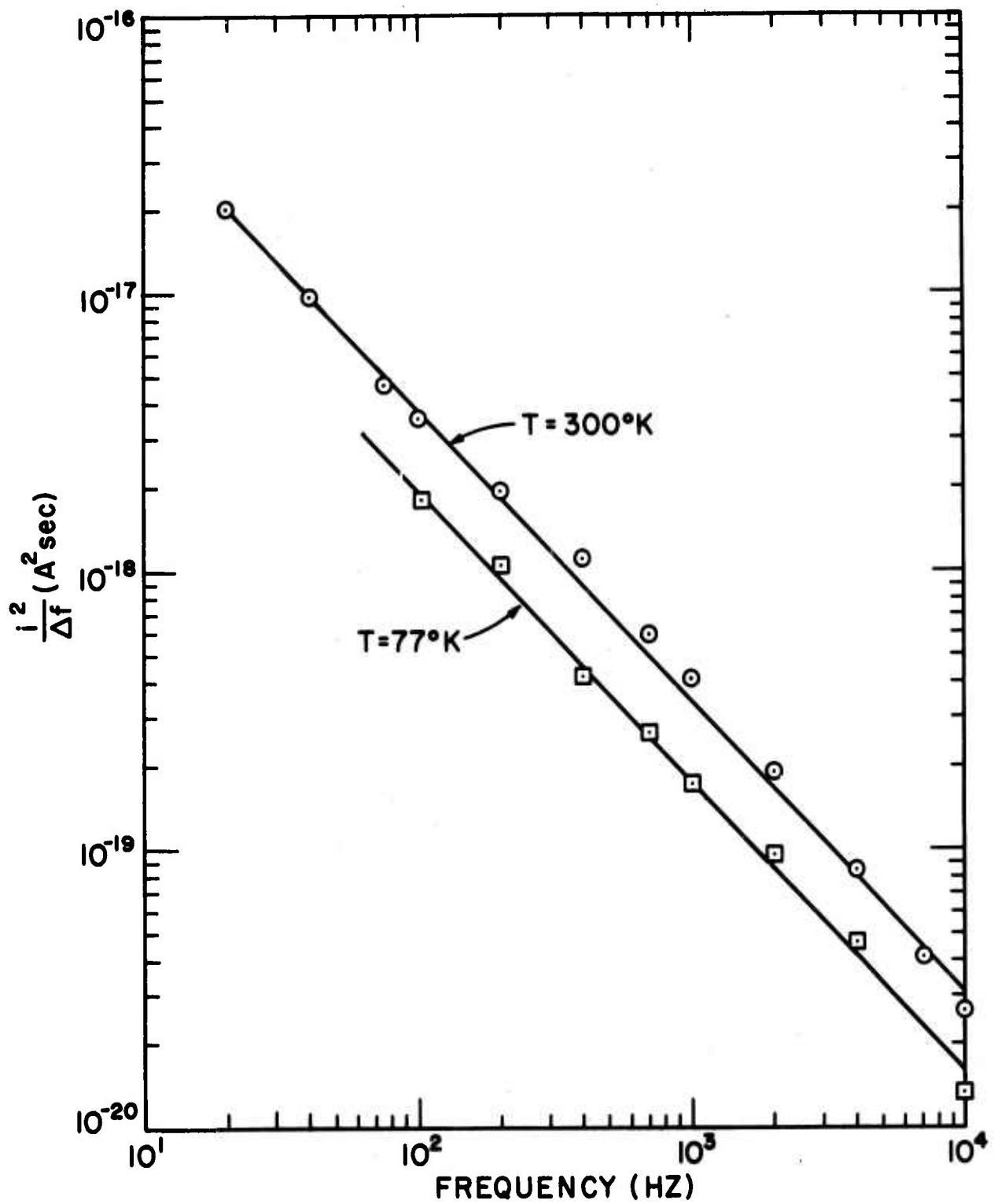and

$$n_{(77°K, \ 15\Omega, \ 4 \ KHz)} = 153$$

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FIGURE 3:   CURRENT NOISE SPECTRA FOR SAMPLE
TE 65-B3 BIASED AT 6. 5 MA

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The two noise ratios differ only by a factor of 1.4 which verifies the expected independency of temperature. When one considers the square law dependence of $i^2/\Delta f$ with bias current (as shown in the last quarterly report), the contact noise hypothesis is strengthened further and therefore continued improvement of the device contacts is warranted.

With regard to other contact noise studies an experiment is underway to evaluate the current noise below threshold as a function of contact perimeter to area ratio. It is expected that the smaller the ratio the lower will be the contact noise contribution. In conjunction with the above experiment will be a study of the actual contact resistance evaluated by two new formulations which will be reported later.

b. Generation-Recombination Noise

The latest series of devices, the TE113's have shown an improvement in both the current noise and FM noise. Preliminary measurements on device TE113-#10 has shown a lower 1/f noise component than most previous devices. Along with the 1/f component, however, there has been noted a plateau region in the noise, in addition to a tendency for the noise to roll-off with the square of frequency. Figure 4 shows the below threshold current noise spectrum for sample #10 taken at room temperature. As indicated, the total curve can be nicely separated into a 1/f component and a generation-recombination (G-R) component with a 3 db roll-off point corresponding to a lifetime of about 10 μsec. If one uses a simple G-R noise formulation and combines the data obtained from Hall measurements, photoluminescence
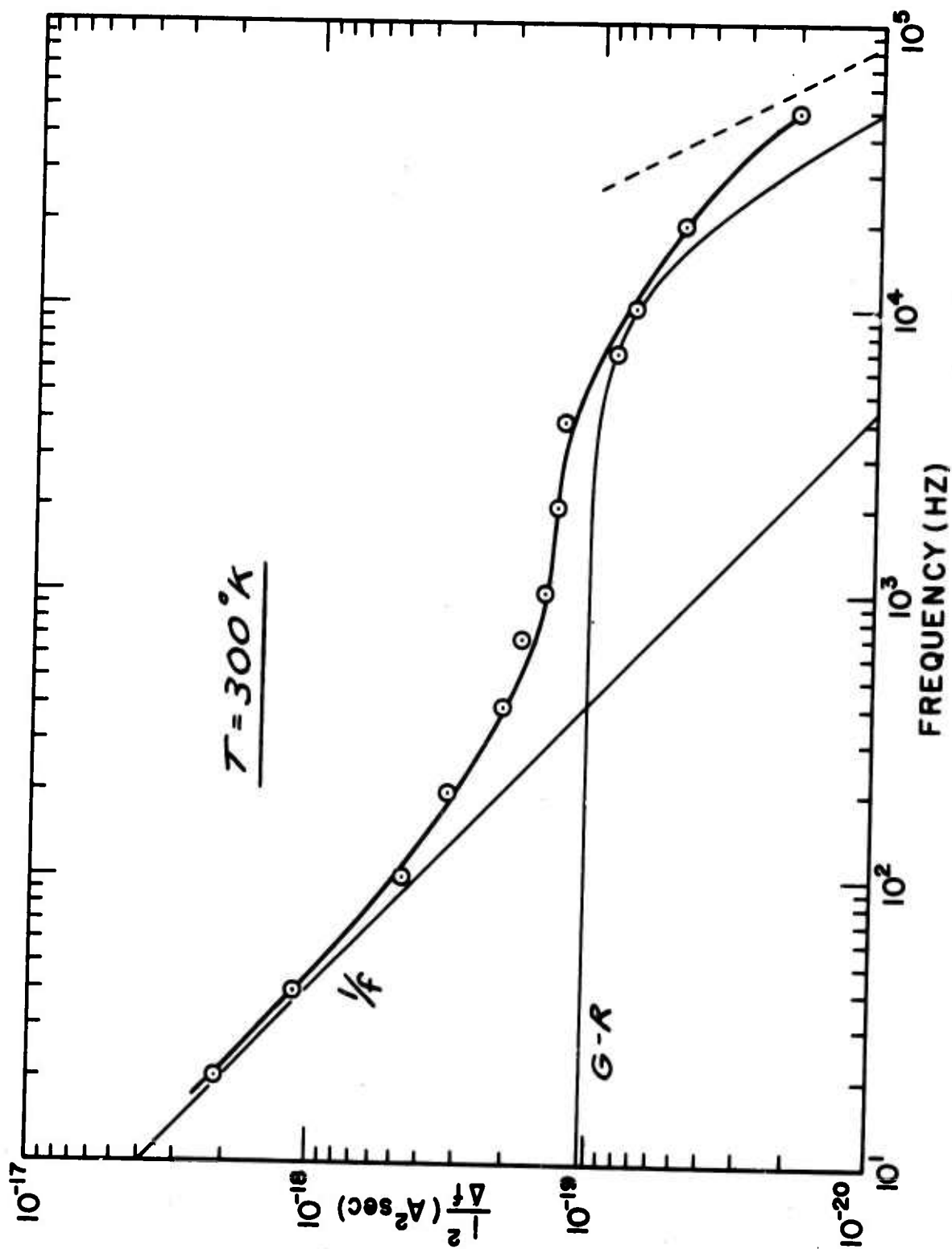
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FIGURE 4: CURRENT NOISE SPECTRUM OF SAMPLE TE 113 #10

AT 300°K AND 5.4 MA BIAS

measurements, and current noise measurements, then the noise roll-off corresponds to a deep donor level at about 0.35 ev from the conduction band. According to simple G-R noise formulation

$$\left(\frac{i^2}{\Delta f}\right)_{plateau} \propto \frac{I^2 \tau}{n_o}$$

and,

$$f_{3\ db\ point} \propto \frac{1}{\tau}$$

where τ is the average noise lifetime, n_o the free carrier density, and $f_{3\ db}$ the roll-off frequency. If the model of a deep lying donor is used then it is found that

$$\tau \propto \frac{1}{n_o}$$

and consequently,

$$\left(\frac{i^2}{\Delta f}\right)_{plateau} \propto \frac{1}{n_o^2}$$

Considering now the effect of temperature, one finds that,

$$n_o \propto e^{-E_d/kT}$$

where E_d is the deep donor energy. Thus,

$$f_{3\ db} \propto e^{-E_d/kT}$$

and,

$$\left(\frac{i^2}{\Delta f}\right)_{plateau} \propto e^{2E_d/kT}$$

Raising the sample temperature should consequently extend the roll-off frequency and lower the noise plateau. In Figure 5, the current noise
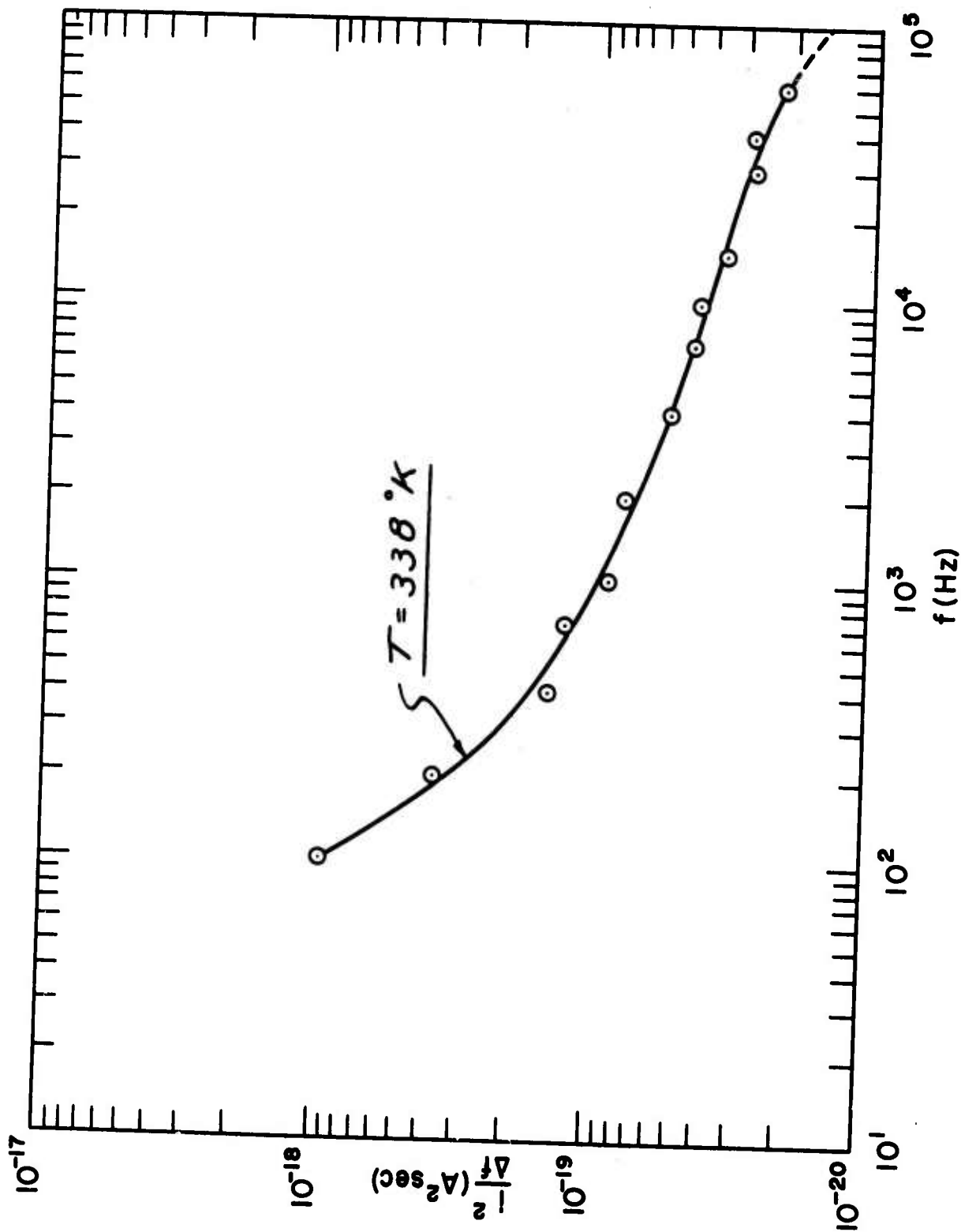
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FIGURE 5: CURRENT NOISE SPECTRUM OF SAMPLE TE 113 #10
AT 338°K AND 6.5 MA BIAS.

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spectrum is shown for sample #10 at 338°K and at the same bias level used for the 300°K spectrum. The noise plateau has indeed lowered and the roll-off tendency has been pushed to a higher frequency--both in good qualitative agreement with the above crude argument.

Further study of this hypothesized deep donor level is being continued and combined with other measurements, the noise studies can be very revealing in the characterization of HPL solution grown GaAs. The presence of a deep lying donor at ≈ 0.35 ev could also be quite important to the device RF behavior.

c. FM Noise

It has already been mentioned that the TE113 devices have shown a large decrease in FM noise from previous devices. By way of comparison, the FM noise spectrum of a typical TE113 sample is shown in Figure 6 along with the FM noise of a standard unlocked klystron signal generator. As shown, the levels are quite comparable with only a few parts in 10^9 frequency deviation at frequencies greater than 10 KHz from the carrier.
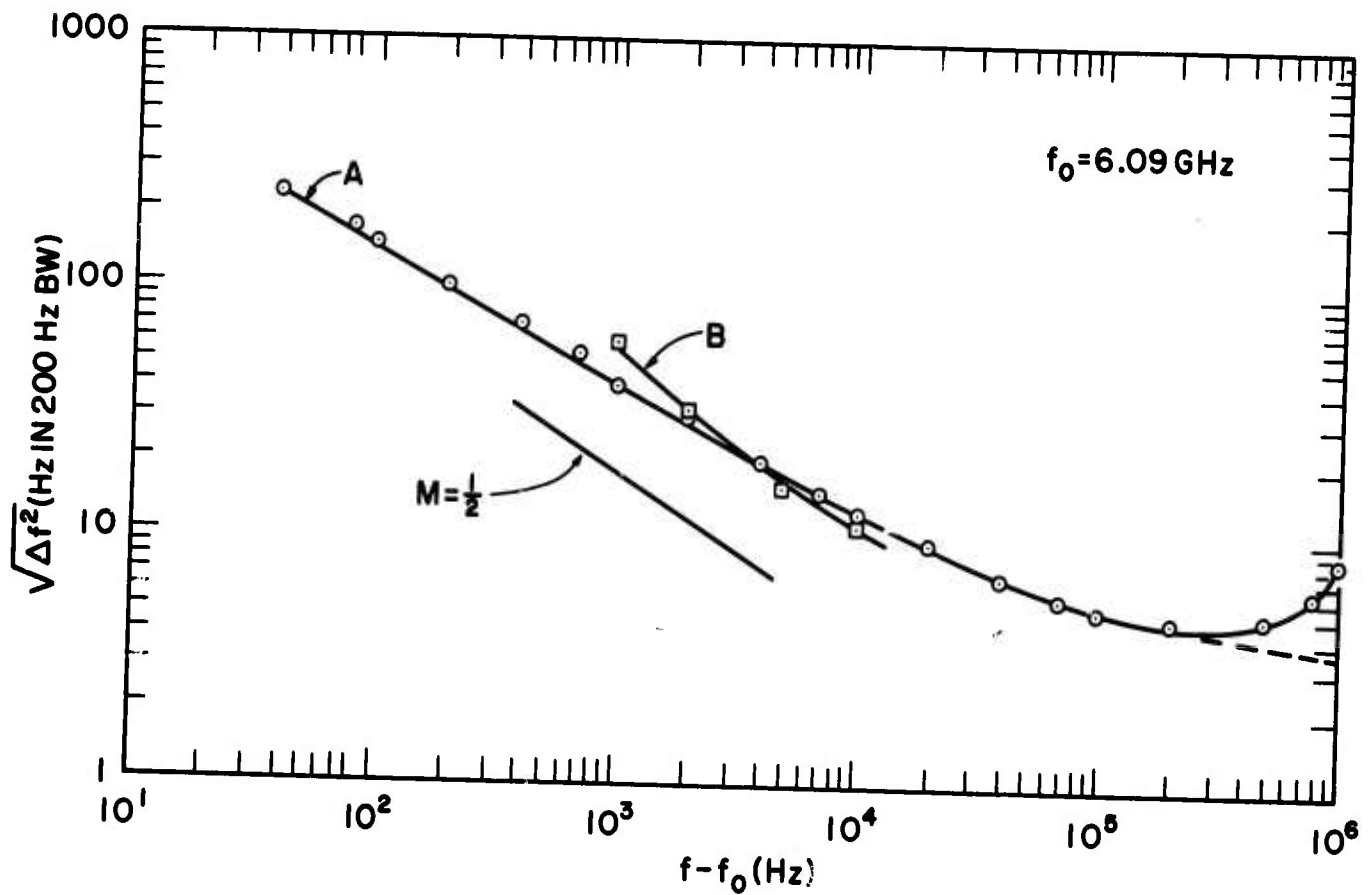
FIGURE 6:

    A) FM NOISE SPECTRUM OF A TYPICAL TE 113 SAMPLE

    B) FM NOISE SPECTRUM OF AN UNLOCKED HP 618A
        KLYSTRON SIGNAL GENERATOR AT 5 GHz

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III.   COMPUTER STUDIES

III. 1   Model Formulation

The most efficient mode of operation of a Gunn effect device is most probably in the bulk negative conductance mode or, practically, the limited space charge accumulation (LSA) mode. In order to achieve a working formulation of device behavior in the bulk negative conductance mode, a simple computer model has been set up and some preliminary results presented below.

The necessary results can best be determined from calculations based on the power absorbed by a single carrier from the dc and rf fields impressed on the device. The circuit used for these computations is the same as shown in Fig. 11A and Fig. 11B of the last quarterly report. If the Q of the parallel resonant circuit is high, the electric field in the device can be expressed as

$$E = E_o + E_1 \, \text{Sin} \, \omega t \tag{1}$$

where E_o and E_1 are the dc and rf electric fields. The powers absorbed by a single carrier from the dc and rf electric fields are given as:

$$P_{dc} = \frac{qE_o}{T} \int_o^T v(E) \, \omega t \, dt \tag{2}$$

$$P_{rf} = \frac{qE_1}{T} \int_o^T v(E) \, \text{Sin} \, \omega t \, dt \tag{3}$$

where $\omega = 2\pi f$, $T = \frac{1}{f}$ and v is the field-dependent velocity of the carrier.

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The dc to rf power conversion efficiency η and the total rf power delivered to the load are given as

$$\eta = - \frac{P_{rf}}{P_{dc}} \qquad (4)$$

and,

$$P_1 = \frac{n_o LA\, qE_1}{T} \int_0^T v(E)\, \text{Sin}\, \omega t\, dt \qquad (5)$$

Where L and A are the length and the cross sectional area of the device and n_o is the carrier concentration.

The negative resistance R and the low-field resistance R_o can be expressed as

$$R = \frac{(E_1\, L)^2}{2\, P_1} \qquad (6)$$

$$R_o = \frac{L}{n_o\, u_o\, Aq} \qquad (7)$$

where u_o is the low-field mobility of the n-type GaAs. The ratio $\dfrac{R}{R_o}$, independent of n_o, L and A, is expressed as

$$\frac{R}{R_o} = \frac{q(E_1)^2 u_o}{2\, P_{rf}} \qquad (8)$$

Equations (4), (5) and (8) are used to obtain numerical results for the power output, conversion efficiency and the load resistance for steady-state sinusoidal oscillations.

III.2   Computer Simulation and Assumptions Involved

In order to study the behavior of bulk-negative-resistance modes of operation, it is necessary to have an easily manipulated velocity-field curve

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for the device. By easily manipulated it is meant that such quantities as peak-to-valley ratio, maximum negative resistance, threshold field and peak velocity can be adjusted easily and relatively independently.

For the present calculations the two-section velocity-field curve shown in Fig. 7 was used. Below threshold field a polynominal curve fit gave very good agreement with the desired curve. The velocity below threshold is expressed as

$$v = K_{11} E + K_{12} E^2 + K_{13} E^3 \qquad (9)$$

where K_{11}, K_{12}, K_{13} are adjusted to give the desired threshold field, peak velocity and velocity saturation. For the present calculations

$$K_{11} = 7.94583$$

$$K_{12} = .492262$$

$$K_{13} = -.316667$$

Above threshold, the velocity is given by

$$v = K_{21} + K_{22} \left(\frac{E + E_{pk} - 2 E_{th}}{E_{pk} - E_{th}} \right) e^{ -\left(\frac{E - E_{th}}{E_{pk} - E_{th}} \right)} \qquad (10)$$

where K_{21}, K_{22}, E_{th} and E_{pk} are as shown in Figure 7.

The velocity-field curve was used to derive design information for LSA mode operation. The assumptions made in these calculations are:

1. The whole sample is either in the negative resistance region or in the positive resistance region.

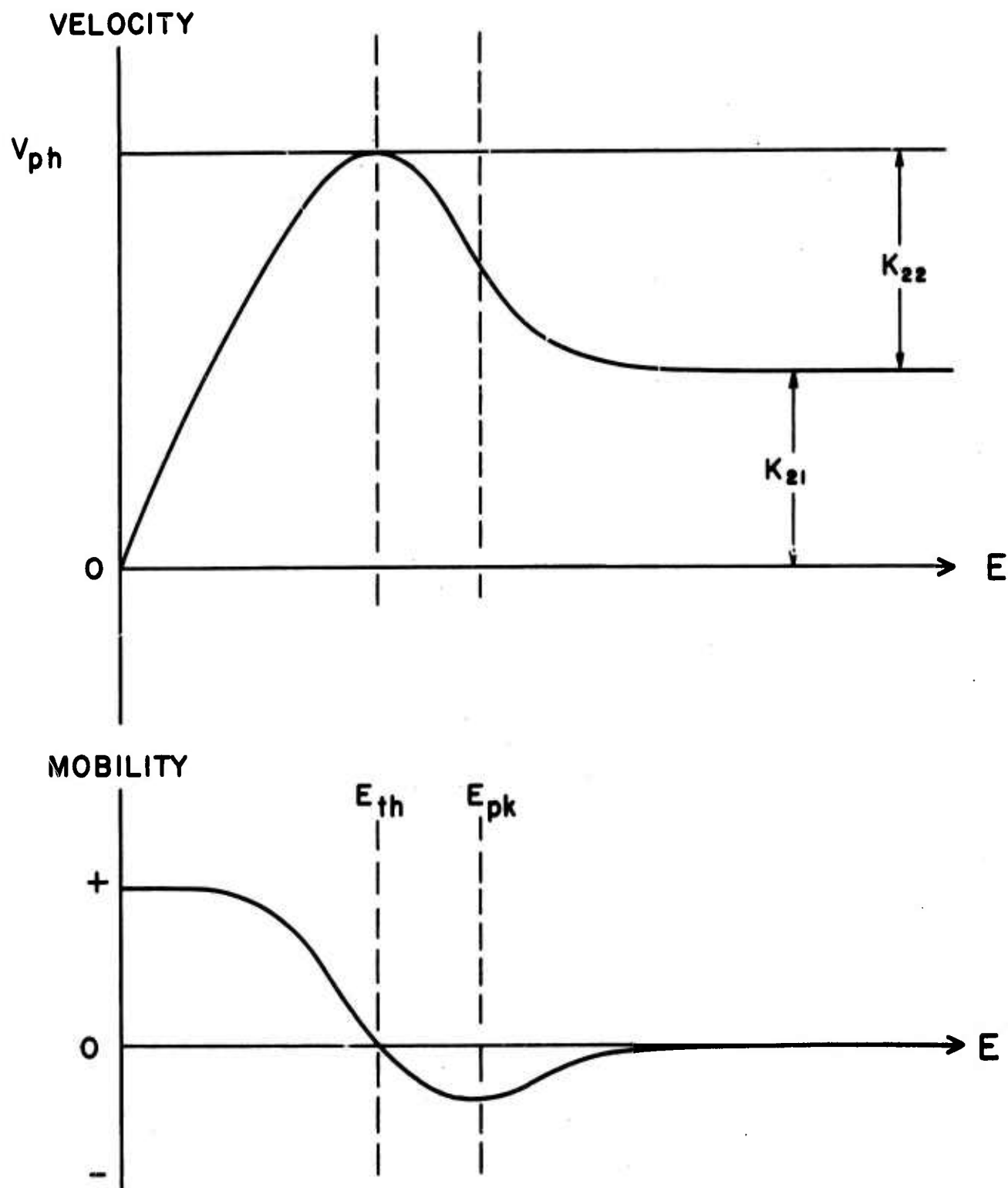2. The applied voltage is sinusoidal.

VELOCITY

V_{ph}

K_{22}

K_{21}

O

E

MOBILITY

E_{th} E_{pk}

+

0

E

−

FIGURE 7: a) VELOCITY VERSUS ELECTRIC FIELD
           b) MOBILITY VERSUS ELECTRIC FIELD

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3. The LSA limit will be calculated by a separate mobility integration and used to define the range of validity of the present design curves.

The problem is handled by a computer program and some initial results of efficiency, relative power output and $-R/R_o$ as a function of bias field, obtained for different values of rf field, are shown in Figures 8, 9, and 10 for a peak to valley velocity ratio of 2. The labels on the curves 1 RF, 2 RF----13 RF correspond to rf field amplitudes of n KV/cm, $n = 1, 2, -- 13$. As can be seen from Figs. 8, 9, and 10, there are combinations of E_o and E_1 for which the carriers deliver power to the rf field and sustain oscillations. A maximum conversion efficiency of 15% is calculated for a peak to valley velocity ratio of 2.

It is obvious that there is a lot of freedom in adjusting the various parameters of interest. Consequently, when an experimental and theoretical check is desired the computations can be easily obtained.

The basic computer setup is such that many different outputs can be obtained. For example, the model of amplitude modulation noise converted to FM noise can be checked theoretically by using curves of

$$\frac{d\left(-R/R_o\right)}{dE} \quad \text{and} \quad \frac{dC}{dR} \quad \text{to obtain } \Delta f_o \text{ versus bias field.}$$

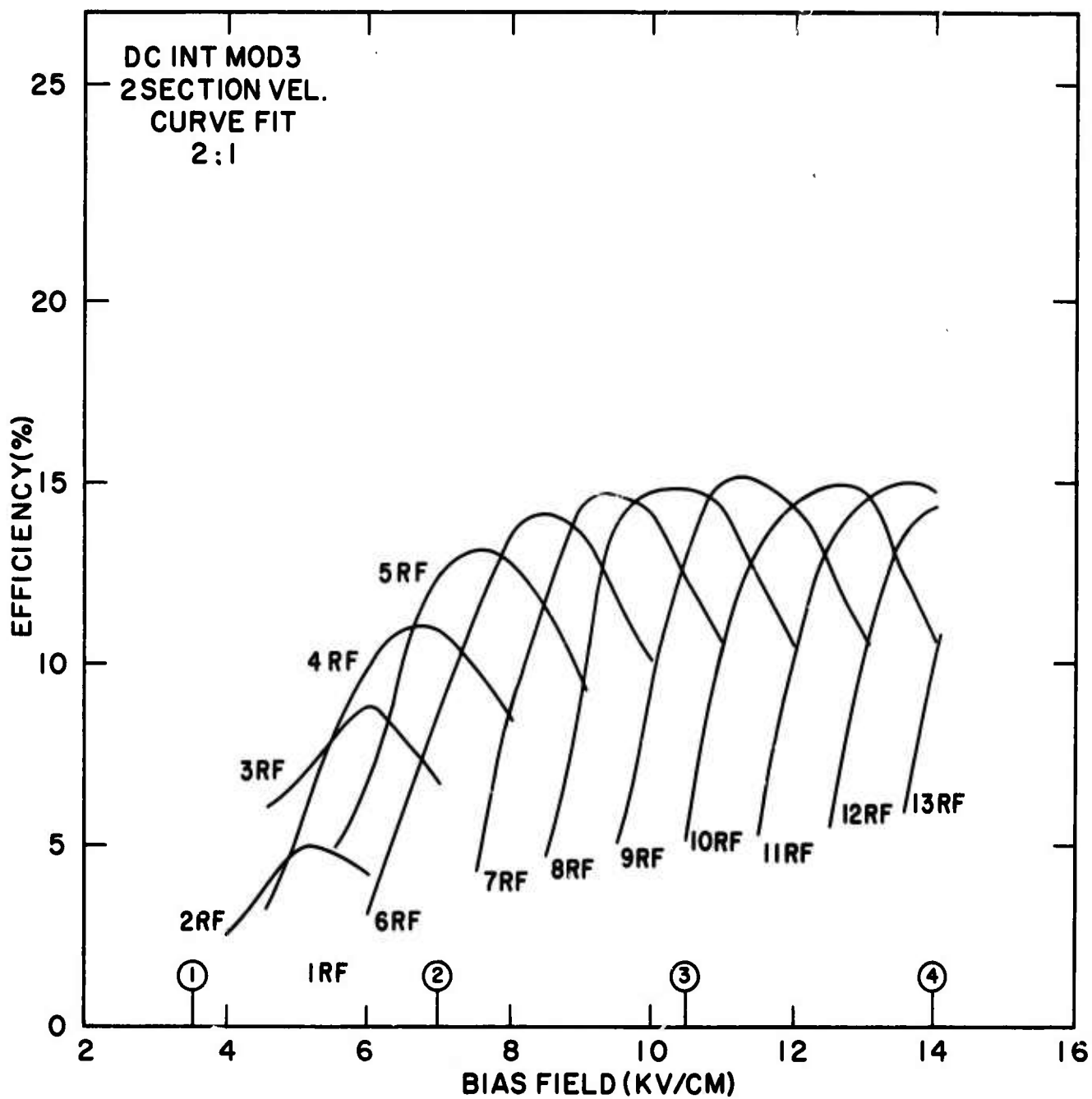More information along these lines will be reported in the future.

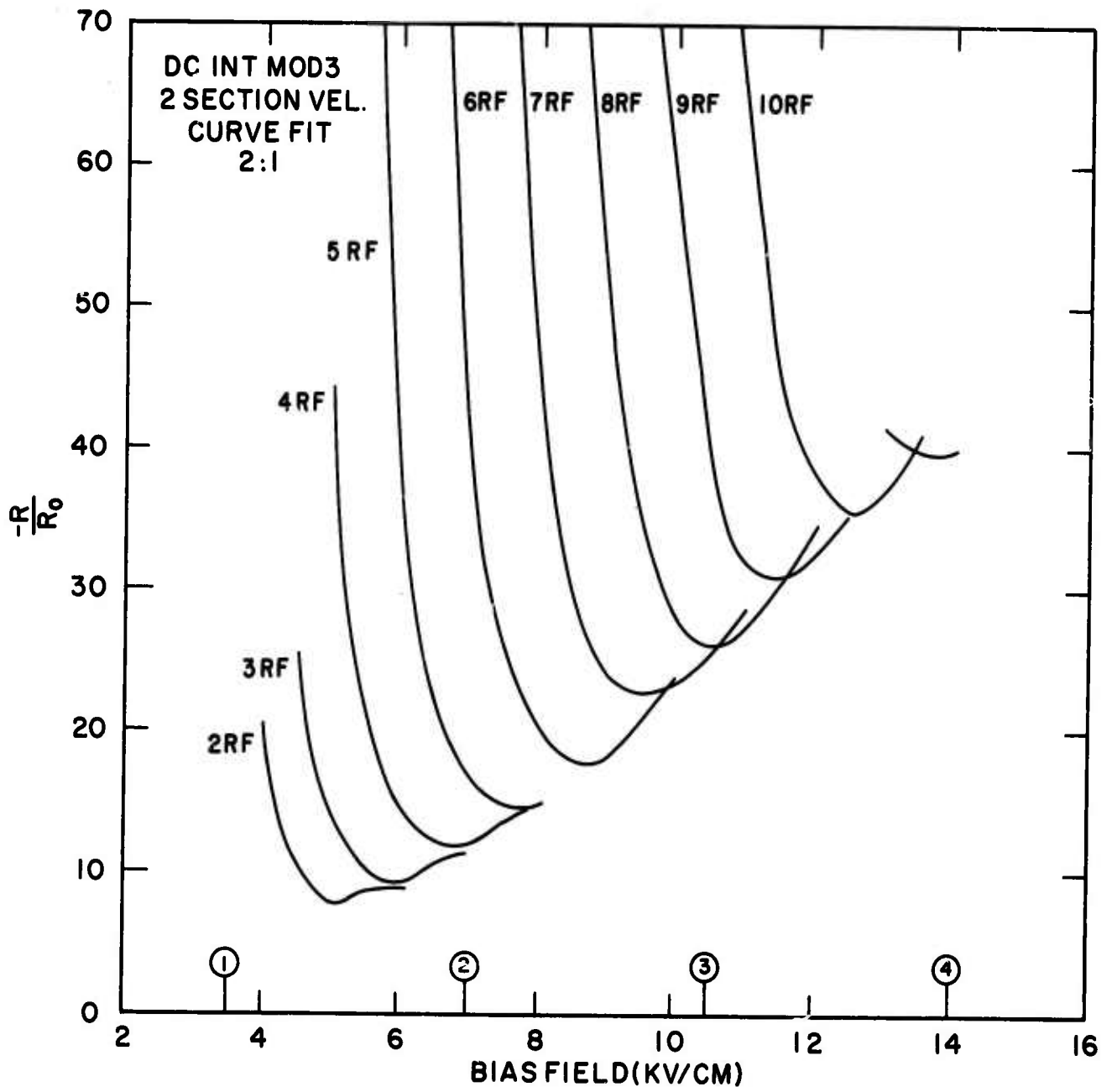FIGURE 8: EFFICIENCY VERSUS D. C. BIAS FIELD

FIGURE 9: NORMALIZED NEGATIVE RESISTANCE VERSUS
D. C. BIAS FIELD
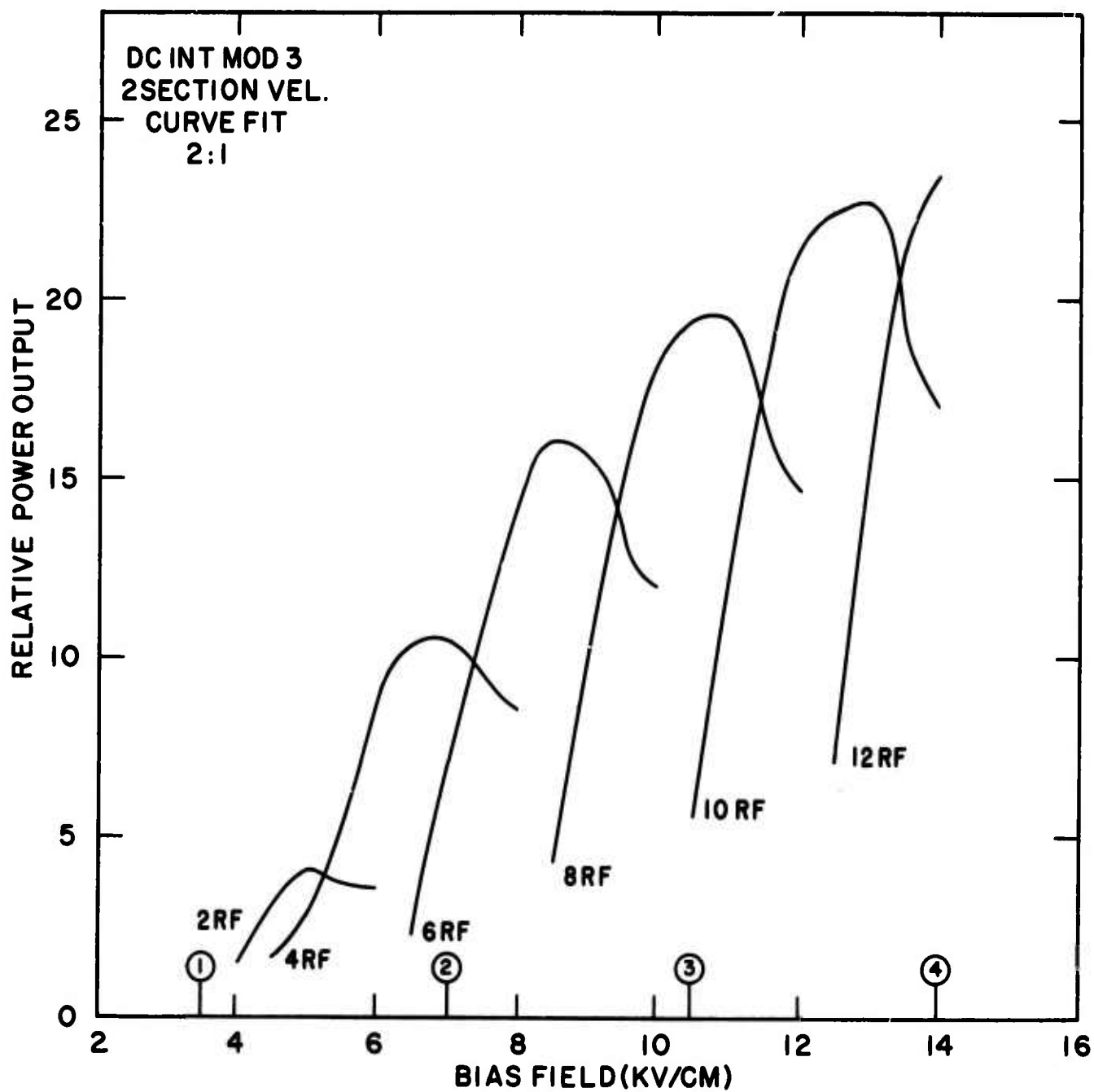
FIGURE 10: RELATIVE POWER OUTPUT VERSUS D. C. BIAS FIELD

IV.   CONCLUSIONS

Continued effort is being made to fabricate better Gunn effect devices from Hewlett-Packard Laboratories solution grown GaAs. Die attaching, heat sinking and external contacting are problems which are very much under control but the actual device geometry and material homogeneity warrant further study.

Future effort will be concerned with obtaining more efficient production of RF power by operating in a bulk negative conductive mode. The preliminary computer results show that the simplified negative conductance model will be helpful in interpreting experimental results.

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13. ABSTRACT

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